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# A MINIATURE SPIRAL BOURDON TUBE PRESSURE TRANSDUCER

by

E. F. Price, A.M.I.E.E., A.F.R.Ae.S.





MINISTRY OF AVIATION
FARNBOROUGH HANTS

U.D.C. No. 621.317.39 : 531.787

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1. Transducers, Pressure


SUMMARY

This Report gives information on the design of a miniature pressure transducer employing a spiral shaped stainless steel Bourdon tube and a deposited track potentiometer. The test results obtained from several models covering different pressure ranges are shown together with an analysis of their performance under different environmental conditions. The Report also discusses the problems likely to be encountered in the design of very low pressure models and suggests a possible line of approach to further development, with particular reference to transducers having a pressure range below about 0/20 lb/in$^2$.


Departmental Reference: IR46

## CONTENTS

## 1 INTRODUCTION

The spiral Bourdon tube pressure transducer described in this Report has been designed as a small size instrument capable of overcoming the major disadvantages generally associated with conventional "C" shaped Bourdon tube transducers i.e. their liability to exhibit large errors when acceleration forces are present and the possibility of their being damaged or de-ranged when subjected to vibration. It has previously been demonstrated[1] that these disadvantages can be overcome by using a twisted Bourdon tube assembly but the resulting transducer is 5 inches long by 1 inch diameter and for particular purposes where size and weight are of importance, this spiral Bourdon tube transducer would be more acceptable. The approximate size of the gauge pressure spiral Bourdon tube transducer is $1\frac{1}{4}$ inches × $1\frac{1}{8}$ inches × $\frac{7}{8}$ inch and it weighs about 2 oz.

## 2 THEORY OF THE SPIRAL BOURDON TUBE

The Bourdon tube being considered takes the form of a spiral of uniformly increasing radius of curvature, with the minor axis of the tube lying in the plane of the spiral. The theory of operation is similar to the "C" shaped tube[2] but it is made more complex due to the continuously varying radius of curvature and to the uneven flattening of the tube, particularly in the first turn, where a greater winding force is required to form the spiral.

The movement of the "tip" or free end of a "C" shaped Bourdon tube when subjected to internal pressure is very complex and none of the theories so far advanced takes into account all the variables involved, such as stress concentration at the pressure connector and the continuous change in curvature during its deflection. The theories do, however, indicate that within close limits the change in angle subtended at the centre by the tube segment is proportional to the change of pressure in the tube.

The "tip" deflection of a "C" shaped Bourdon is proportional to the arc length of tube employed and this also applies in the case of a spiral Bourdon tube. A "C" shaped tube with a radius of curvature of 0.75 inch and included arc of 270 degrees will have a "tip" movement of approximately 0.13 inch. A spiral tube of the same cross-section with an average radius of curvature of 0.75 inch and included arc length of 1000 degrees (3 turns) has a "tip" movement of about 0.5 inch, representing an angular movement of some 30 degrees.

During the development of this particular transducer it has been proved possible by careful design and suitable heat-treatment processes to produce

Bourdon tube pressure elements which have a substantially constant cross-section throughout their length, and as a result the movement of the indicating device attached to the tube spindle is linear throughout the pressure range of the transducer.

## 3 DEVELOPMENT OF THE MINIATURE SPIRAL BOURDON TUBE CONFIGURATION

### 3.1 Principle of operation

The transducer in its simplest form consists of a Bourdon tube sealed at one end and coiled into a spiral somewhat similar to the mainspring of a clock (Fig.1). The outer open end is fixed to the transducer case and the sealed inner turn of the tube is attached to a spindle which is supported between bearings. When pressure is applied to the open end of the tube the turns of the spiral move relative to one another and as a consequence the spindle rotates. The spindle can be made to operate a potentiometer wiper or any other suitable device and the degree of change in position of the indicator will be a measure of the pressure applied to the transducer. In this design both ends of the tube are restrained against unwanted movement in the plane of the spiral so that the effects of acceleration forces are greatly reduced. Conventional transducers with "C" shaped tubes have only one end of the pressure responsive element fixed and are therefore liable to show large errors when subjected to vibration and acceleration forces.

### 3.2 Choice of tube material

The transducer was designed to be capable of measuring the pressure of corrosive liquids such as HTP. The Bourdon tube and its associated pressure fittings were, therefore, made from a compatible material. Stainless steel AISI 316 (EN58J) was chosen since it had previously been proved satisfactory when used with corrosive media, and in addition, has reasonably good Bourdon tube characteristics. AISI 316 stainless steel has the best corrosion resisting properties of the several materials available for use as Bourdon tubes, but other materials have superior spring rates and temperature coefficients. Where HTP compatibility is not a particular requirement the Bourdon tube could, with advantage, be made from Ni-Span-C which is an age hardened alloy of nickel, chrome and iron to which titanium has been added. Seegers[3] gives the following table of relative ratings of Bourdon tube material properties:-

| Material | Resistance to corrosion | Spring rate | Temperature coefficient | Hysteresis | Total* |
|---|---|---|---|---|---|
| Beryllium copper | 1 | 6 | 1 | 6 | 14 |
| AISI 316 stainless steel | 6 | 2 | 1 | 2 | 11 |
| Chrome molybdenum steel | 1 | 4 | 1 | 4 | 10 |
| Ni-Span-C | 5 | 5 | 6 | 5 | 21 |

*The higher the rating the better the material property.

For low pressure measurements AISI 316 can be formed into a tube with a maximum diameter of 0.25 inch and a wall thickness, at this diameter, drawn down to 0.0005 inch. A tube having these dimensions and subsequently rolled into a Bourdon section with a major axis of 0.354 inch and a minor axis of 0.045 inch will, according to Goitein[4], have an approximate pressure range of 0 to 0.5 $lb/in^2$. Goitein's formula, which gives good results in practice, is as follows:-

$$f_{max} = \left(\frac{P}{2}\ \frac{A}{t}\right) + \left(\frac{A - B}{t}\right)^2$$

where $f_{max}$ = maximum stress ($lb/in^2$)

$P$ = internal pressure ($lb/in^2$)

$t$ = wall thickness (inches)

$A$ = mean major axis (inches)

$B$ = mean minor axis (inches).

The maximum value of the permissible stress in stainless steel AISI 316 is 75,000 $lb/in^2$ [5] but the spiral tubes used in this design of transducer are worked at a much lower value so as to obtain the best possible linearity, hysteresis and repeatability performance.

## 3.3 Rolling and forming spiral tubes

A selected length of stainless steel tubing is first rolled into the cross-section as shown in Fig.2. After having been formed to this shape the

tube is wound into a spiral of the correct size and spacing and the end of the inner turn welded to seal off the tube, after having ensured that any low-melting point filling alloy which may have been used in this process is completely removed from the tube interior. During the winding process great care must be taken to avoid forming corrugations, kinks or other discontinuities in the tube and to see that an even spacing is maintained between the turns of the spiral.

A machine for producing spiral tubes, with wall thicknesses varying from 0.0005 inch to 0.025 inch is shown in Fig.3. All the tubes used in the numerous experimental transducers of this type were wound on this machine and no difficulty has been experienced in maintaining the correct shape, spacing and performance of the spirals, although the undoubted skill of the operator should not be overlooked. The end of the sealed inner turn of the spiral is prepared as shown in Fig.4 and subsequently fastened to the transducer spindle by means of a "Selock" pin as shown in the drawing.

### 3.4 Stabilising and stress relieving the spiral Bourdon tubes

During the winding process it is most essential that the spiral be frequently heat-treated to ensure that the tube material is not being excessively work-hardened and to help in preventing additional tube flattening which may occur if unnecessarily large winding forces are used. After the spiral has been wound it must be finally heat-treated at the correct temperature to remove local stresses and to ensure a constant Young's modulus throughout the whole length of the tube. A considerable amount of experimental effort was necessary to make multi-turn stainless steel Bourdon tubes with good linearity, hysteresis and repeatability characteristics and with an overall spiral diameter not exceeding 0.875 inch. By careful appraisal of the heat-treatment processes coupled with the use of a specially designed jig for filling the tube with low melting point alloy, it has been proved possible to make spiral Bourdon tubes with five turns and an overall diameter approximately 0.875 inch. The turn to turn spacing is of the order 0.010 inch and the major to minor axis ratio about 5 : 1.

Spiral tubes have also been made from beryllium copper where the processes involved are very similar to those required for stainless steel; the main differences are in the temperatures necessary for the various heat-treatments and the amount of "spring-back" to be allowed during the winding of the coil.

## 4 DEPOSITED TRACK POTENTIOMETERS

### 4.1 Design features

During the early design studies of this transducer it became apparent that a number of advantages were possible by incorporating a deposited track potentiometer instead of the more conventional wire wound unit. Three of the most important features associated with deposited track potentiometers are (a) freedom of choice regarding the substrate or former shape, (b) the ability to have the oxide track laid down to any preferred contour, (c) continuous resolution. Early experimental models of the spiral transducer were fitted with disc-shaped deposited track potentiometers made from borosilicate glass about $\frac{3}{4}$ inch diameter and 1/16 inch thick. The edge of the disc was flame polished to give a slightly convex shape and the oxide film deposited around part of the periphery Fig.5(a). A specially designed gold-alloy potentiometer wiper made contact with the edge of the disc to form the pickoff. The potentiometer disc was attached to the spindle and rotated as the transducer was pressurised; the stationary wiper in this case was fastened to an insulated panel fitted to the body of the transducer. This style of potentiometer was not proceeded with because an alternative design having a rectangular substrate with curved deposited oxide track afforded better facilities for ranging the instrument by varying the effective radius of the arm to which the potentiometer wiper is attached. These latter type potentiometers had been developed by Messrs G.V. Planer Ltd under a Ministry of Aviation contract; they are made from polished "Pyrex" glass and have the ends of the track accurately defined by rhodium plated sections flush with the oxide film. The potentiometer terminating leads are soldered to the extremities of these rhodium sections and are additionally secured by an epoxy resin. The wiper stylus associated with the flat type of potentiometer is made from a gold-silver-copper alloy which is compatible with the oxide track and in addition has been proved to have good wear characteristics combined with minimum rotational noise and ease of fabrication. The actual style of wiper evolved for use with the flat deposited track potentiometer is shown in Fig.5(b).

### 4.2 Electrical specification

The electrical specification defining the performance of the deposited track potentiometers is as follows:-

Resistance 1500 ohms ±10 per cent.

| | |
|---|---|
| Linearity | No error to exceed 0.15 per cent of full scale. |
| Noise | The noise output voltage not to exceed 0.01 per cent of the applied voltage. |
| Potentiometer life | Minimum of 100 000 sweeps without deterioration of linearity or increase in noise level. |
| Maximum voltage | 12 volts dc. |
| Active length | approximately 0.125 inch. |

4.3 Environmental specification

The environmental specification for the deposited track potentiometers is as follows:-

| | |
|---|---|
| Shock test | 100g for 5 milliseconds. |
| Vibration | 30 c/s to 5000 c/s at a level of 10g. |
| Temperature range | $-40^{\circ}C$ to $+80^{\circ}C$. |

Additionally, the potentiometers must operate satisfactorily when immersed in silicone fluid, or in dry conditions without silicone fluid.

## 5 CONSTRUCTION OF SPIRAL BOURDON TUBE TRANSDUCER

### 5.1 Constructional materials

The case of the transducer may be constructed from either a corrosion-resistant steel or a stable aluminium alloy which can be anodised to give surface protection. In the latter case a considerable saving in weight can be effected, but the Bourdon tube and its associated pressure fittings must be made from a material compatible with the media being measured. In the models so far constructed the tube and fittings have been made from AISI 316 (EN58J) which is the best all round material for this purpose.

### 5.2 Transducer spindle bearings

The function of these bearings is to support the ends of the spindle or arbor which positions the inner turn of the spiral tube assembly. It is of paramount importance that the bearings be of the highest quality with the lowest possible friction and "breakaway" torque so as not to impair the performance of the transducer. The bearings ultimately chosen for this purpose are manufactured by the Barden Corporation of America, who hold the patent for this particular type of bearing. They are made of stainless steel with the stainless steel balls pocketed in PTFE, a solid, low-friction non-deteriorating material which replaces

the oil or grease generally employed in conventional bearings. Double dust shields are fitted to assist in keeping out foreign matter and to help preserve the bearing performance which is so important in this particular application.

Insofar as the transducers may be held in store for long periods, the absence of a conventional lubricant is an advantage.

5.3 Bourdon tube pressure element

As previously mentioned in this Report, the Bourdon tube is coiled into a spiral so that the dimensions of the transducer can be kept to a minimum and in addition the advantages associated with a long active length of tube can be fully exploited. In general, the size of a Bourdon tube pressure transducer is related to the length of tube which can be accommodated within the instrument case. For a "C" shaped tube a compromise is made whereby a tube of modest length, $2\frac{1}{2}$ inches to 3 inches is used in combination with a mechanical lever system or other form of multiplying device to give the required movement to the potentiometer wiper or such alternative form of pressure indicator as may be employed. In the spiral Bourdon transducer a pressure tube approximately 12 inches long is used but due to its compact form the complete transducer can be kept to a small size. Fig.6 is an "exploded" sketch showing how the tube and its associated fittings are positioned relative to the transducer case.

5.4 Installation of spiral Bourdon tube transducer

To facilitate installation, the transducer has been arranged so that the potentiometer leads are brought out via terminals which are adjacent to the pressure inlet connector as shown in Fig.7. Hence only one side need be accessible and "side by side" mounting of a number of transducers can be achieved with a consequent saving in space requirements.

6 PERFORMANCE

A number of models of the transducer covering different pressure ranges have been made in Instrumentation and Ranges Department model shop and the performance characteristics obtained from these transducers are shown in the following table of results:-

| Pressure lb/in$^2$ | Maximum errors (per cent of full scale) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Linearity | Hysteresis | Repeat-ability | Shock test 100g | Steady 30g acceleration | Vibration 10g 30 c/s to 5000 c/s | Temperature -40°C to +80°C |
| 0/2400 | 0.5 | 0.8 | 0.2 | 0.1 | 0.3 | ±3.5 | -1.2 hot<br>-0.8 cold |
| 0/2000(i) | 0.2 | 0.4 | 0.1 | 0.2 | 0.5 | ±3.0 | +2.5 hot<br>-2.2 cold |
| 0/2000(ii) | 0.3 | 0.5 | 0.2 | 0.1 | 0.2 | ±3.0 | +2.5 hot<br>-2.1 cold |
| 0/250(i) | 0.2 | 0.6 | 0.2 | 0.3 | 0.7 | ±2.0 | +2.1 hot<br>-2.5 cold |
| 0/250(ii) | 0.3 | 0.3 | 0.1 | 0.5 | 0.3 | ±4.0 | +2.8 hot<br>-2.3 cold |
| 0/30 | 0.3 | 0.4 | 0.3 | 0.5 | 1.5 | ±4.0 | +2.2 hot<br>-0.8 cold |

The linearity, hysteresis, repeatability and temperature test results are self explanatory, but some further explanation is necessary about the other tests.

The "shock" tests were made on a drop-tester which is designed to subject the transducer to a deceleration of 100g during a period of 5 milliseconds. The transducer was dropped in all three axes and the results as tabulated show the maximum calibration shift produced by this particular test. In all cases the maximum shift occurred when the transducer was dropped at right angles to its normal mounting position. Fixing the transducer with its base horizontal to the mounting bracket reduces the drop-test shift.

The 30g steady acceleration tests were carried out on a centrifuge and the output of the transducer was monitored on a precision decade box via the centrifuge slip-ring assembly. About half full scale pressure was applied to the transducer and retained therein by means of a valve which was fixed to, and rotated with, the centrifuge table. The change in transducer output from the static condition to the reading obtained at the same applied pressure under an acceleration of 30g was then recorded. A mounting jig was made which enabled the transducer to be secured in any desired position and the test results shown in this Report are the maximum errors obtained when the transducer was mounted

in its most sensitive position, i.e. when the plane of the spiral is parallel to the centrifuge table and the pressure connector pointing in the direction of rotation.

All the vibration tests on the transducer were made at a level of 10g and covered the frequency range 30 c/s to 5000 c/s. The transducers were vibrated in all three axes and the errors shown were the maximum exhibited by the transducer during a resonance occurring at about 2000/2500 c/s. At other frequencies the vibration errors were considerably less than those recorded in the table of test results.

## 7 PROPOSALS FOR FURTHER DEVELOPMENT

It is considered that with additional development both absolute and differential transducers can be made without greatly increasing the size of the transducer case. In the differential version two identical spiral tubes would be used connected to concentric spindles. One spindle would position the potentiometer wiper whilst the other spindle would vary the position of the potentiometer track according to the pressures applied to the Bourdon tubes. The absolute model would have one of the two tubes at the vacuum reference whilst the other would be available for measuring the varying pressure.

In the case of ultra low pressure spiral transducers, development will show that the use of the "rigid-beam"[6] type of torsion suspension would have worthwhile advantages and could replace the ball bearings used in the present models. The "rigid-beam" suspension is a flexurally rigid torsion member which does not have to be in tension as does the "taut-band" system. In its symmetrical arrangement it consists of a cruciform cross-section and is able to deflect through 25 degrees without the maximum shear stress in the torsion members exceeding the endurance limit in shear. This type of suspension is virtually frictionless (the friction being only the molecular friction of the material, generally beryllium copper).

In the present design of spiral transducer, the wiper stylus associated with the deposited track potentiometer is 0.008 inch diameter and the contact end is polished to a hemispherical shape. The most suitable wiper pressure has been found to be about 4 grams but when designing these very low pressure transducers it may also be necessary to consider employing a lighter wiper pressure so as to reduce the torque (about 0.33 gm/cm for a wiper pressure of 4 grams and a rotational radius of the wiper tip of 1 cm)[7]. If this is done, some form of damping will be required in order to reduce the errors due to vibration. The deposited track potentiometers, as previously mentioned in this

Report, are suitable for use when immersed in silicone fluid and this liquid could, therefore, be used as the damping, medium.

## 8 CONCLUSIONS

The performance results detailed in Section 6 of the Report show that this design of miniature spiral tube transducer is capable of good overall accuracy and that in particular the errors due to vibration and acceleration are of a low value. The pressure range of this type of transducer using Bourdon tube presently available from British sources is from about 30 $lb/in^2$ to 2500 $lb/in^2$ and this compares favourably with existing GW transducers with a more conventional tube configuration. The physical size and weight of the transducer have been kept as small as possible so that it can be considered for those applications where space is limited, and where the transducer weight must be of a low value.

Further development may be necessary in the case of very low pressure models (below about 20 $lb/in^2$) and a possible approach to this investigation is the use of the "rigid-beam" torsion suspension together with some form of internal damping of the transducer mechanism. It is considered that with some additional development, both absolute and differential pressure models of this transducer can be constructed using duplex tubes mounted on concentric spindles.

## 9 ACKNOWLEDGEMENTS

The author wishes to put on record his appreciation of the help and assistance given by Mr. A.W. Hiorns, formerly of the "Transducer Group, Instrumentation and Ranges Department. Credit is due to Mr. E.N. Smith, 37 Dept, R.A.E. for the spiral winding machine design, and to Mr. S. Nettleingham 38 Dept, R.A.E. for micro-welding techniques.

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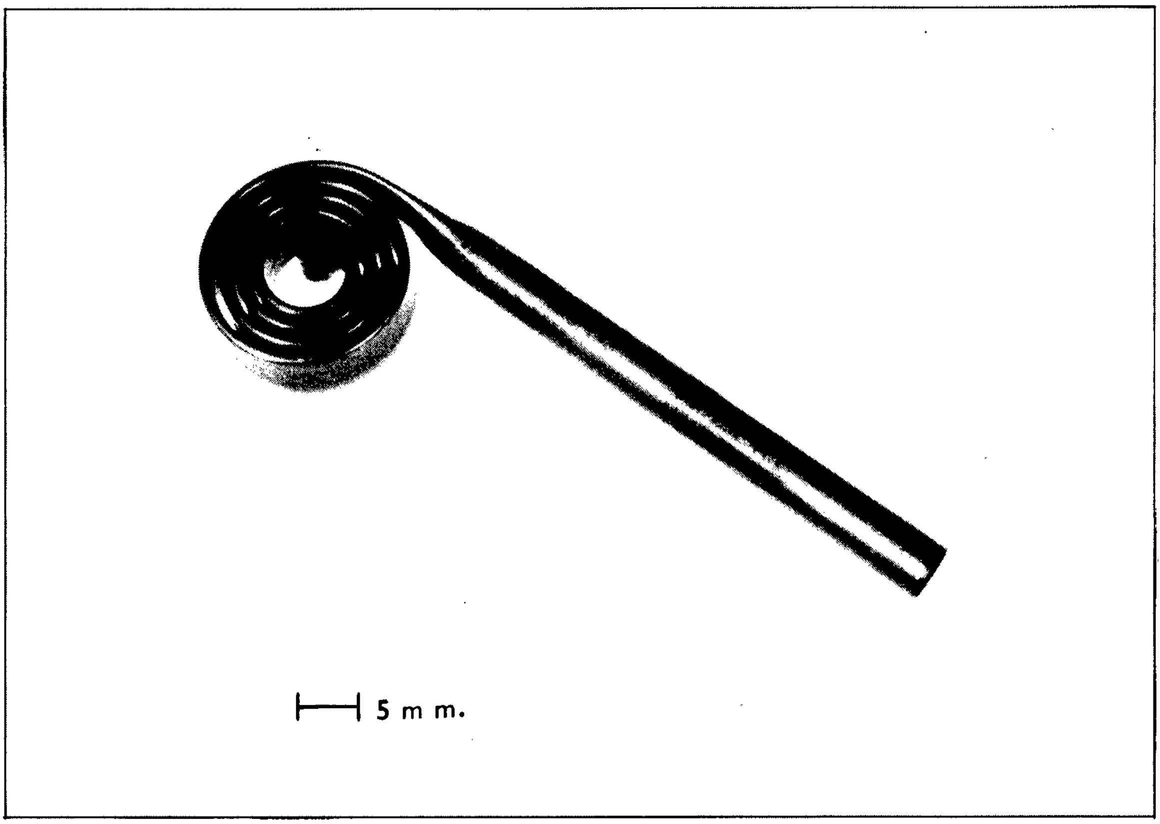



Fig. 1. Spiral Bourdon tube

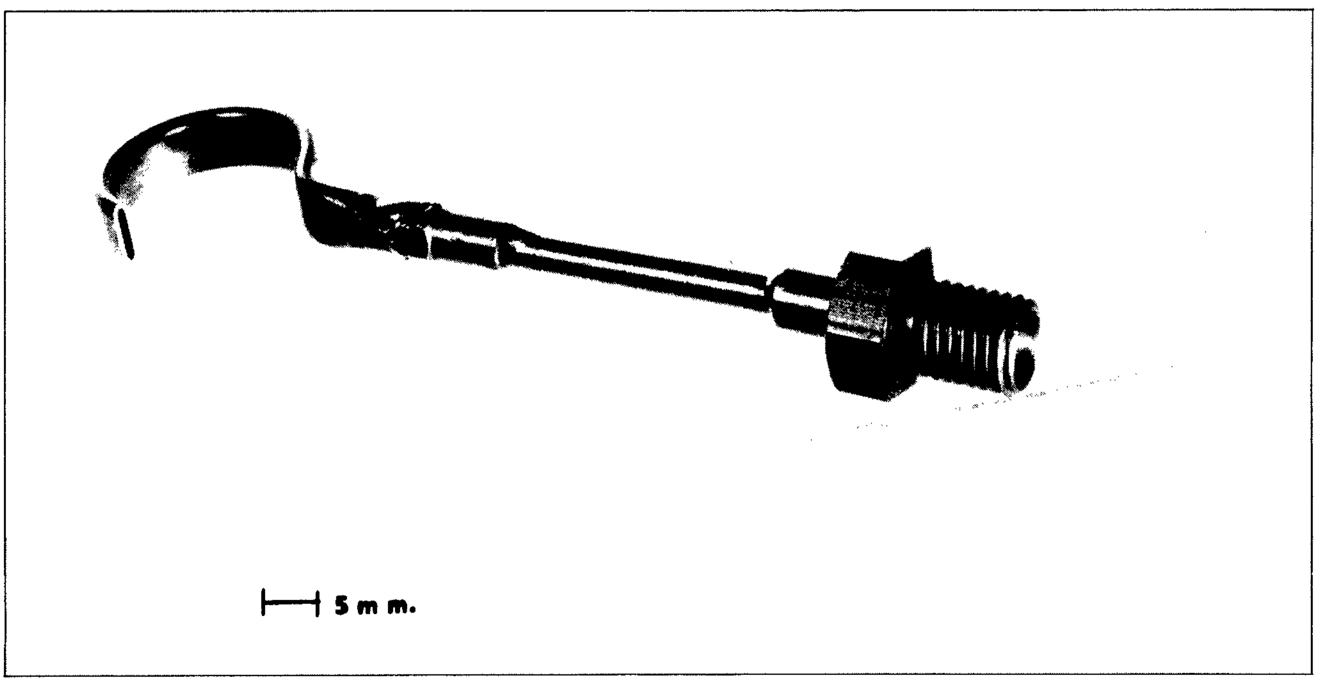



Fig. 2. Section of Bourdon tube

Neg. No. 168728

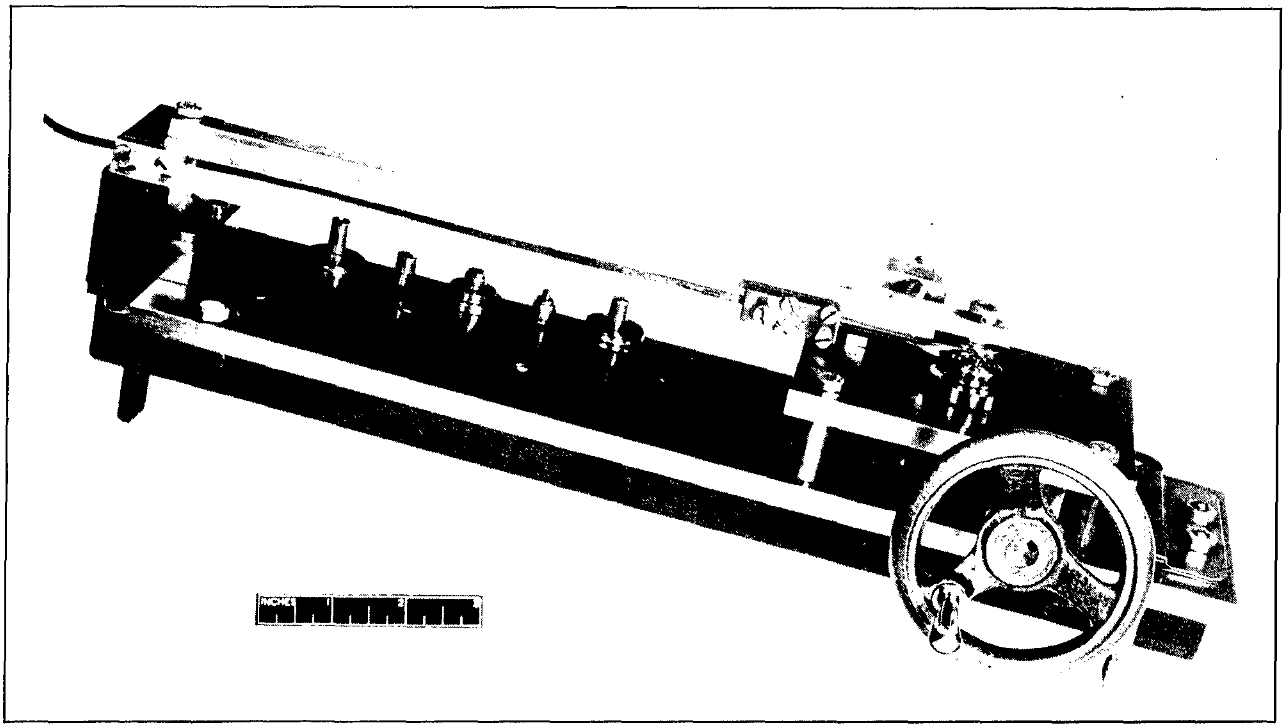


Fig. 3. Bourdon tube Rolling and Coiling machine

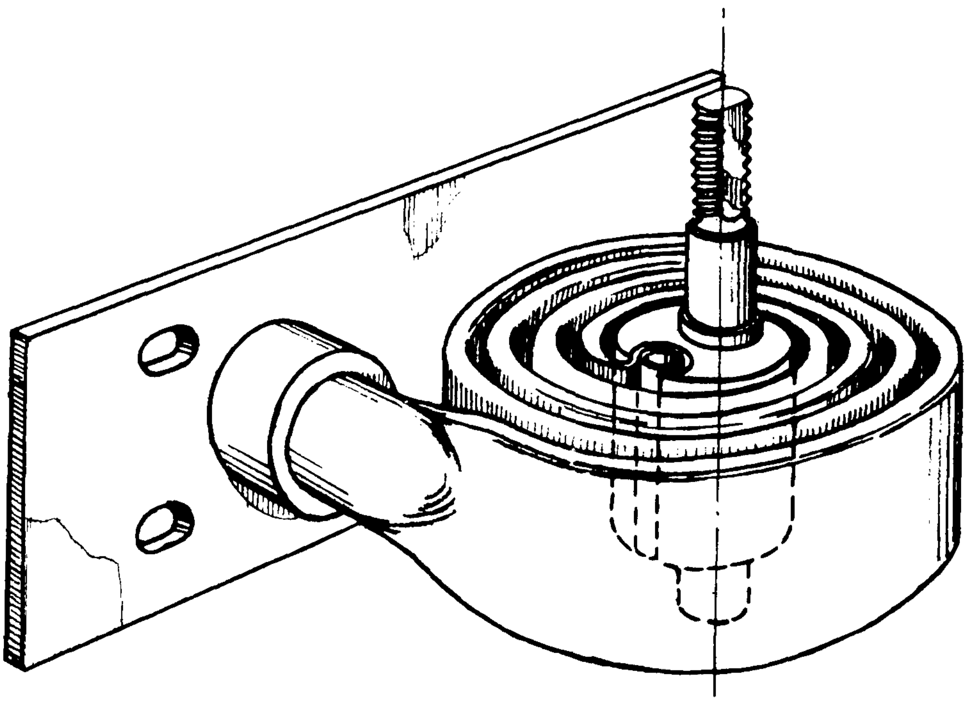


Fig. 4. Method of fixing Bourdon tube to operating spindle

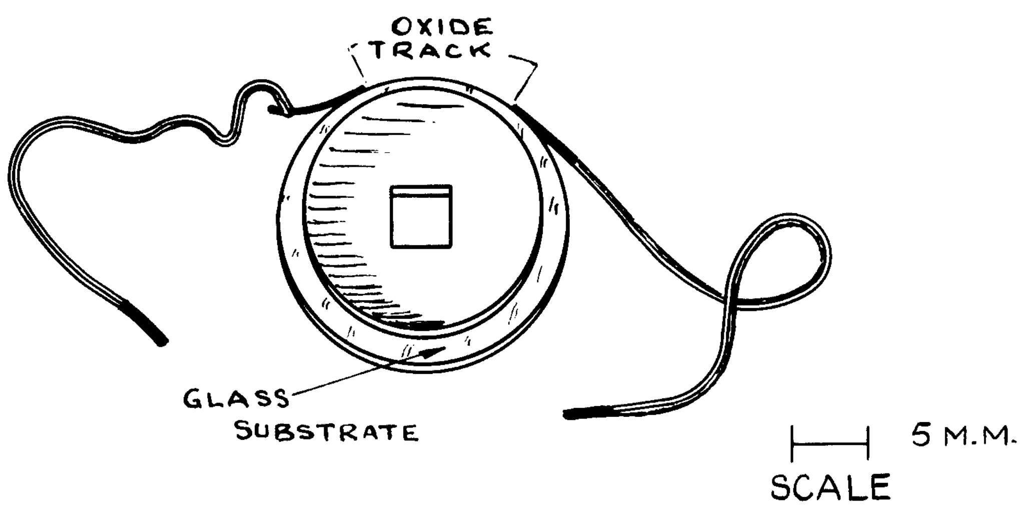
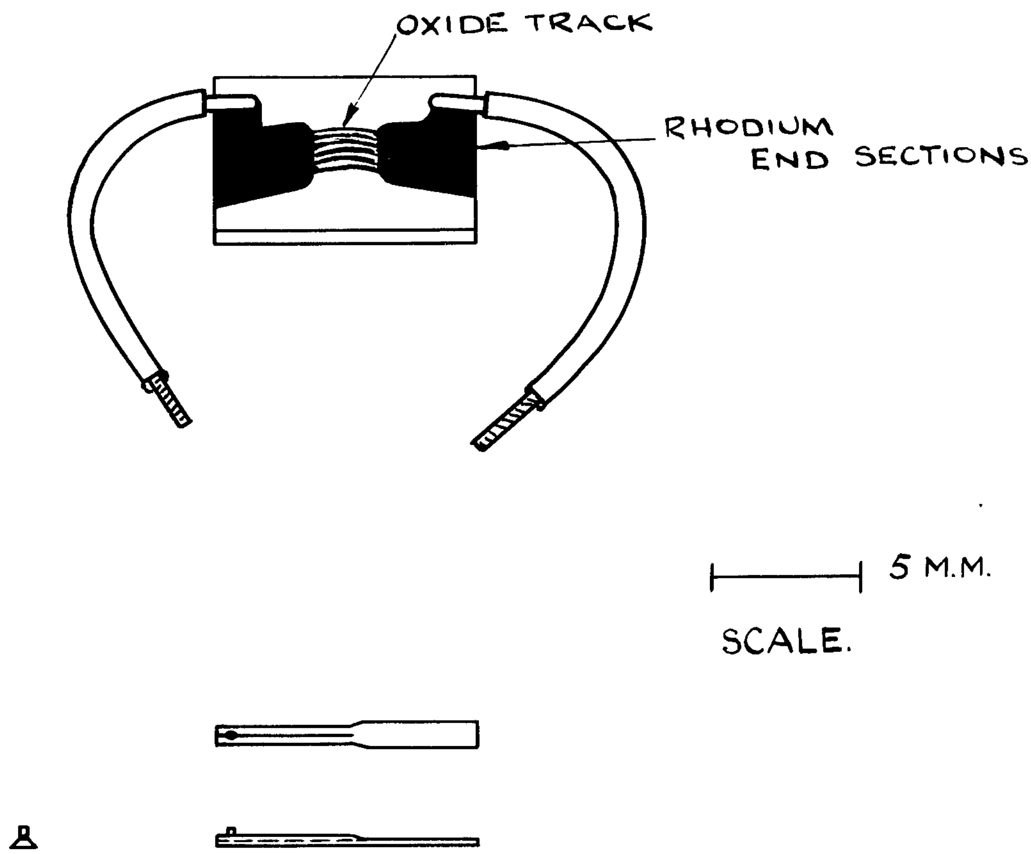



FIG. 5. (a)




WIPER DETAILS (RECTANGULAR TRACK)

FIG. 5. (b)

FIG. 5. (a & b) DEPOSITED TRACK POTENTIOMETERS SHOWING DISC AND RECTANGULAR TYPE SUBSTRATES.

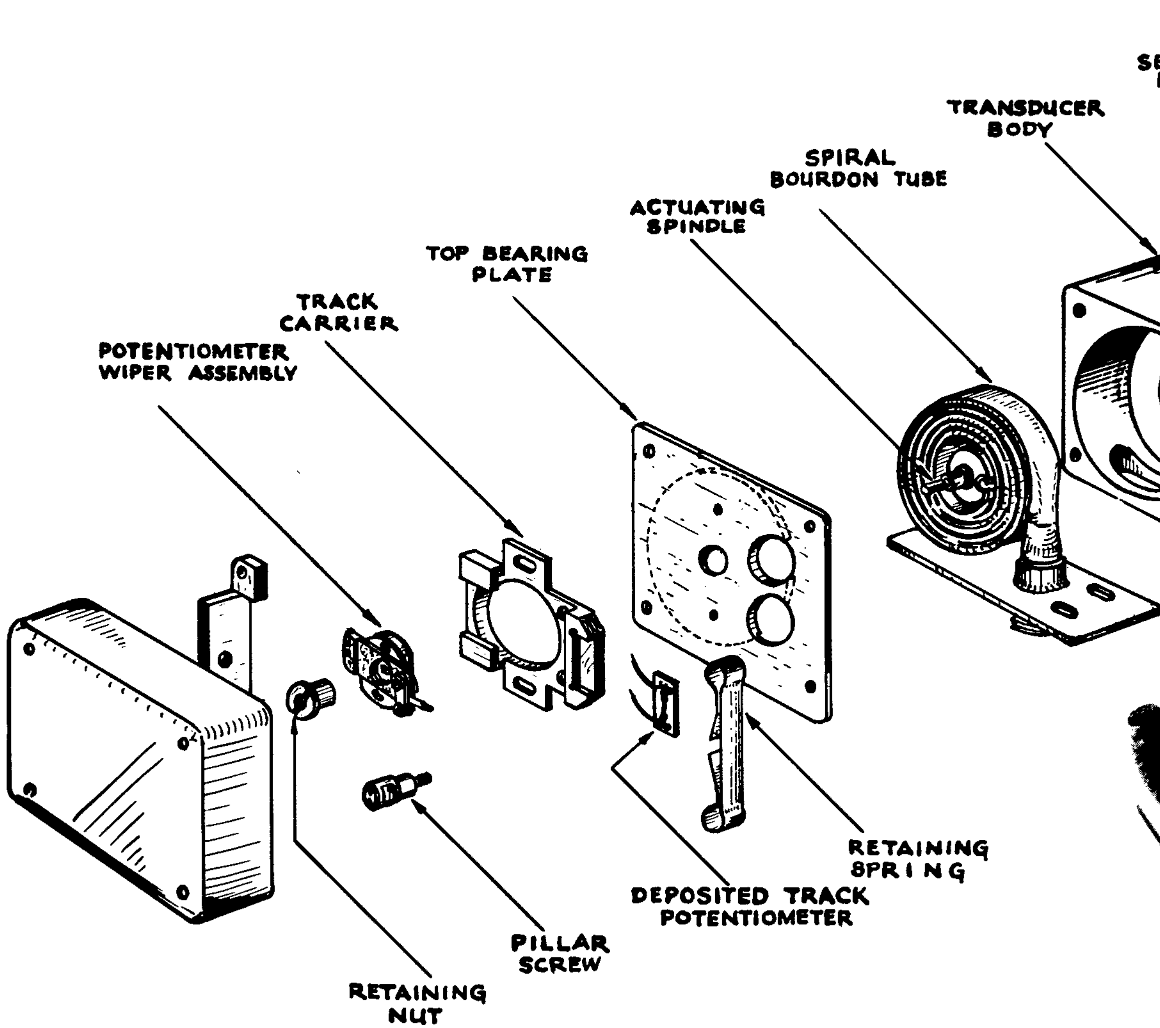
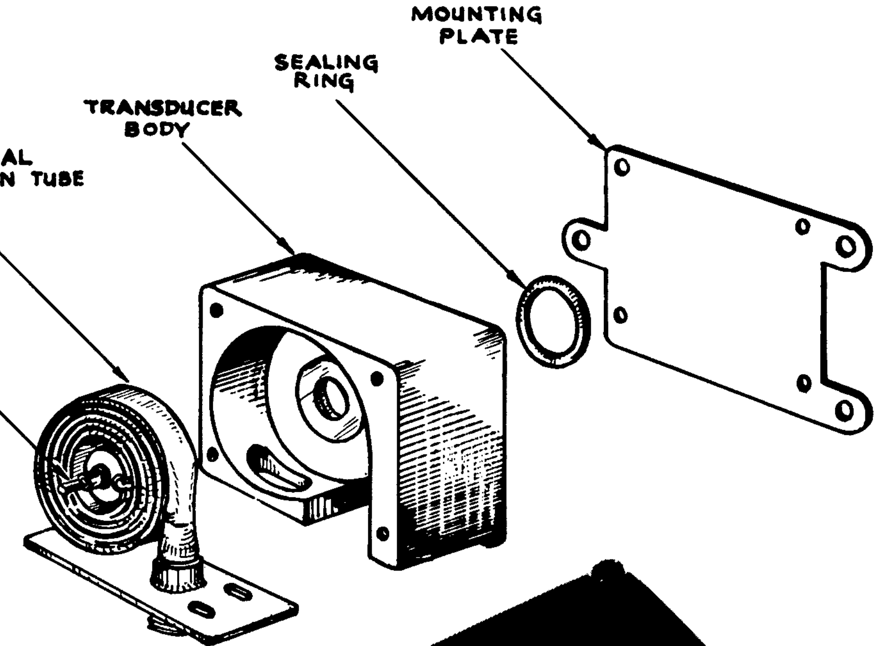




Fig. 6. Miniature spiral Bourdon tube transducer

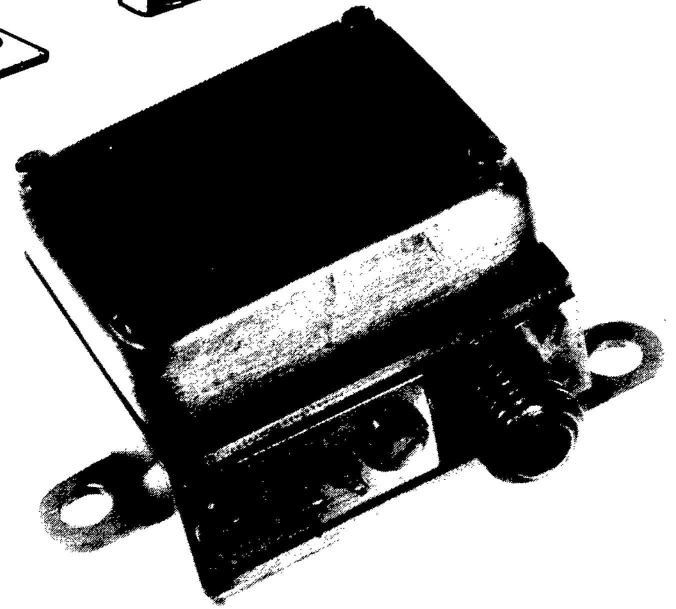



Fig. 7. Miniature Spiral Bourdon tube transducer with centre spindle and deposited track Potentiometer

## DETACHABLE ABSTRACT CARDS

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